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THE EFFECT OF ADMIXTURES AND PROTECTIVE PAINTS ON THE RATE OF CORROSION OF STEEL EMBEDDED IN CONCRETE

Final Report on Research

for

THE BUREAU OF YARDS AND DOCKS

Navy Department

Contract No NBy-10556

by

VIRGINIA ENGINEERING EXPERIMENT STATION

VIRGINIA POLYTECHNIC INSTITUTE

Prepared by:

C. W. Smith
Principal Investigator

Directed By

D. H. Pletta
Project Supervisor

July 15, 1959

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INTRODUCTION

Research on the protection of steel against corrosion by thin precast concrete sections was begun at Virginia Polytechnic Institute in September of 1947. On April 28, Contract N8onr527 was awarded to the V. P. I. Research Foundation by the Office of Naval Research. A final report was made on August 20, 1950 on that project.

The aforementioned contract was extended under the auspices of the Bureau of Yards and Docks of the Department of the Navy as Contract NOy-22981 and a final report was filed on November 14, 1953. This contract was extended from July, 1953 until January, 1955 in order to provide for further tests. A report on the results was made on June 1, 1955.

A further extension of Contract NOy-22981 from February 1, 1955 until June 30, 1956 was then made to include further tests and analysis. A final report on these tests, analyses and a summary of the entire program was made on September 1, 1956. In this report, the original contract, and the three contract extensions noted above, were referred to as Projects I through IV respectively.

On November 12, 1956 a new Contract NBy-10556 was negotiated in order to provide for further tests and analyses. The following report is a final report on the research carried out under this contract. It will be referred to as Project V. The purpose of Project V was to carry out a prescribed set of tests to determine the effect of coatings on steel and concrete and of admixtures in the concrete upon the corrosion rate of the embedded steel.

<u>Concrete Mix</u> - The tests carried out in Project V involved two replications of six batches, each batch of which consisted of 8 test panels and 6 cylinders. The physical properties of the aggregates employed are listed in Table I and were identical for all batches.

TABLE I

Aggregate	Percent Coarser Than Sieve No.							Fineness Modulus
	3/8	4	8	16	30	50	100	
Petersburg Sand	0	0	0.2	18.3	59.3	87.1	96.6	2.615
Crushed Dolomite	0	0	1.3	71.4	99.2	100	100	3.719

	Specific Weight lb/ft^3	Bulk Specific Gravity	Percent Absorption
Petersburg Sand	98	2.52	1.65
Crushed Dolomite	91	2.61	1.91

The properties of each batch are listed in Table II below.

TABLE II

Properties of the Concrete Mixes

Repl No.	Batch No.	Type of Water	Admixture	Flow Factor	Slump in (in.)	Ult. Strength in Compression (6)	Secant Modulus at 1/3 Ult. Str.(6)
I	1	Fresh	None	135	8.75	4350	4.30×10^6
	2	Fresh	Plastiment+	147	8.63	4410	4.39×10^6
	3	Fresh	$CaCl_2$*	150	8.50	4420	4.56×10^6 (5)
	4	Salt	None	128	7.00	4240	4.27×10^6
	5	Salt	Plastiment+	138	7.50	4770	3.89×10^6
	6	Salt	$CaCl_2$*	131	7.00	5030	3.93×10^6
II	1	Fresh	None	144	8.50	4270 (5)	5.69×10^6 (5)
	2	Fresh	Plastiment+	147	8.38	4600	4.12×10^6 (4)
	3	Fresh	$CaCl_2$*	144	8.50	5030	4.13×10^6
	4	Salt	None	131	7.00	4500 (5)	3.98×10^6 (5)
	5	Salt	Plastiment+	140	7.50	5140	4.46×10^6
	6	Salt	$CaCl_2$*	135	7.00	4880	3.96×10^6

+ - Plastiment added at proportion of 3/4 lb. per bag of cement and water reduced at proportion of 1/2 gal. per lb. of plastiment.

* - $CaCl_2$ added in amount of 2% by wt. of cement.

(4) - Avg. of four readings

(5) - Avg. of five readings

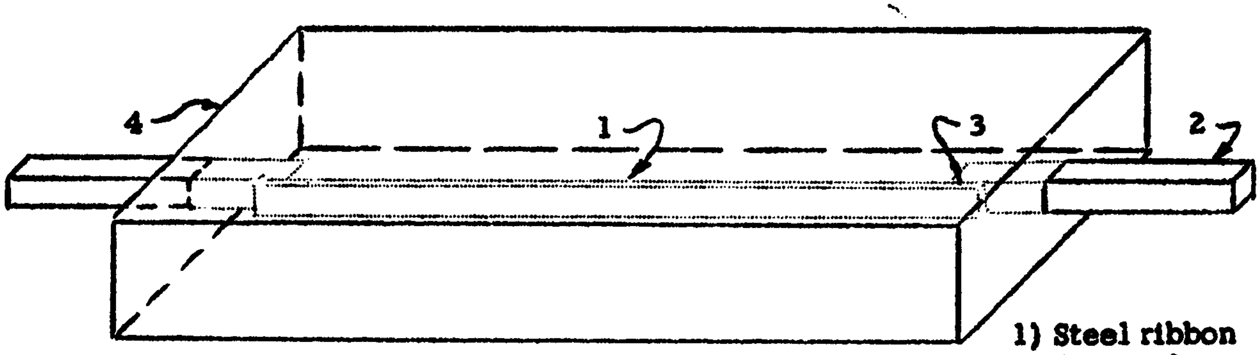
(6) - Avg. of six readings

Batches 1 and 4 consisted of a cement-sand-stone proportion of 1:2.54:0.668 by weight and a water-cement ratio by weight of 0.684, and batches 2, 3, 5 and 6 were modified according to the notes in Table II. The flow factor was determined in accordance with ASTM C87-47 specifications.

All panels and cylinders were subjected to the following curing cycle:

a) In molds at 100% RH and 75°F for two days,
b) In fog room at 100% RH and 75°F for fourteen days, and
c) In controlled room at 50% RH and 70°F for at least twelve days and until tested.

Test Panels Before Project V was initiated, all specimens of the previous project indicating considerable corrosion were broken open and the thin steel ribbons were inspected. In every case, the corrosion was concentrated at the soldered juncture between the steel ribbon and the copper end-bars used for electrical connections. These junctures had been covered with two coats of RSX-100, a thermo-plastic paint made by the Royal Chemical Corporation of Miami, Florida before the ribbons were cast in the concrete specimens. All specimens were 2-3/4 inches wide by 12 inches long by either 3/4 or 1-1/4 inches thick.

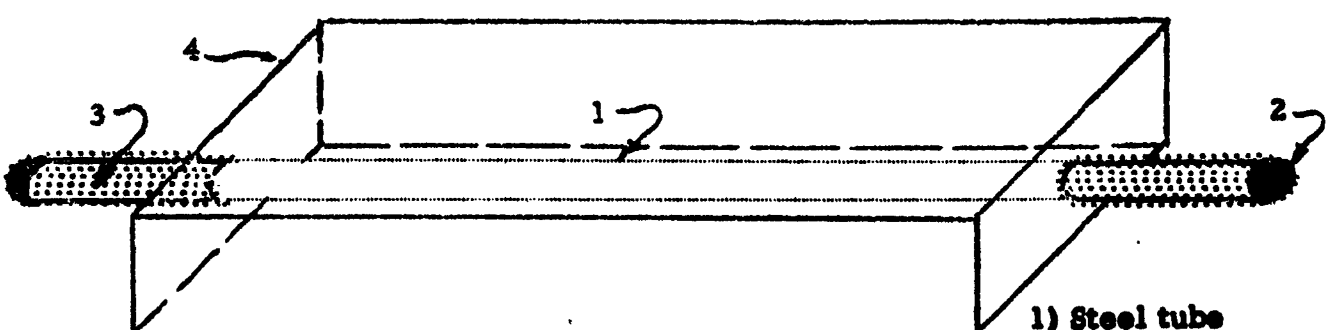


1) Steel ribbon
2) Copper bar
3) Soldered joint
4) Concrete specimen

Specimen Used in Project IV

Figure 1

It was suspected that electrolysis at the coated juncture points might have contributed to the measured corrosion to an undetermined degree. In order to eliminate the contribution of the soldered juncture to the measured corrosion, the copper-steel element was replaced by a single low carbon drawn steel tube (Figure 2) embedded in concrete specimens measuring 2-3/4 by 9 by either 3/4 or 1-1/4 inches.



1) Steel tube
2) Rubber plugs
3) Tube coating
4) Concrete specimen

Specimen Used in Project V

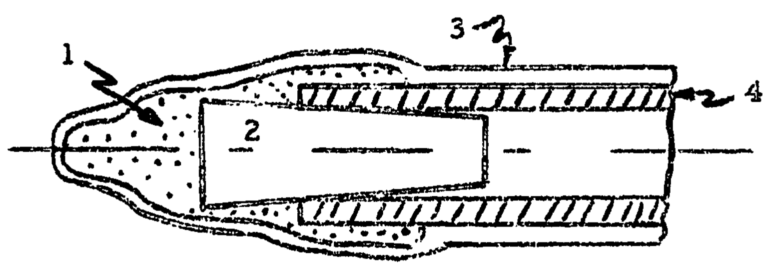
Figure 2

A number of methods were investigated for sealing the ends of the tubes.

Electrical connections at either end of each projecting tube were provided by welding a wire around the tube near the inside edge of the tube for the voltage connection. The resistance connection consisted of specially built banana plugs inserted in the ends of the tubes outside of the voltage connection.

Trial specimens with various types of plugs coated with several different "waterproof" coatings were prepared along with specimens for which the projecting tube ends were flattened and coated with various coatings. These trial specimens were then placed in the cyclic apparatus used in previous projects, and tested through 44 cycles of wetting and drying. As a result of these tests, one set of 12 trial specimens, prepared identically, showed no leakage when measured and examined. Consequently, the method used for preparing these specimens was adopted for the tests of Project V. The method followed is outlined below:

1. The ends of tube were closed with a plug set as shown in Figure 3.
2. The ends of tube were dipped in Sika Seal obtained from Sika Chemical Corporation, Passaic, N. J. and allowed to dry. (Tubes were cleaned with carbon tetrachloride prior to the coating operation.)
3. After concrete specimens were prepared and cured at 100% R. H. and 70° F. for 2 days, the end faces of the specimens were dipped in Sika Transparent, a silicone water repellent resin manufactured by Sika Chemical Corporation, Passaic, N. J.
4. After replacing the plugs, which were removed for each reading, the ends of the tubes were dipped in Microcrystalline Wax obtained from the Bareco Wax Company, Tulsa, Okla. The waxes used were Ceraweld Amber, B Square 170/175 Amber and Ceratek 155, the properties of which were about the same for sealing purposes.



1) Medical Serum Tube Cap
2) Rubber plug
3) Wax coating
4) Coated tube

End Plug

Figure 3

<u>Protective Treatments and Notation:</u> One concrete coating, one steel coating, two admixtures, two types of water, and two cover depths were used in the tests. In order to include the effects of each of the above and their interactions, 48 test panels were made for each of two replications. Table III lists the various treatments accompanied by the notation used.

TABLE III

Level	Concrete Coating	Steel Coating	Admixture	Water	Cover Depth
0	E_0-None	F_0-None	B_0-None	H_0-Fresh	D_0 = 1/4"
1	E_1-Paint+	F_1-Paint++	B_1-Plastiment	H_1-Salt	D_1 = 1/2"
2			B_2-$CaCl_2$		

+ E_1-Paint - Sika Transparent, a colorless water repellent made from silicone resins, manufactured by Sika Chemical Corporation, Passaic, N. J.

++ F_1-Paint - Sika Seal, a solution of natural and petroleum asphalts, plasticizing, adhesive, and vapor compounds.

Paint E_1 was applied by brush after the panels had been cured for 16 days at 100% R. H. and 75° F., followed by 12 days at 50% R. H. and 70° F. Paint F_1 was applied by dipping each end of the tubes in the paint, which was thinned with 10% ethyl gasoline by volume. Each tube was cleaned with carbon tetrachloride before dipping. The paint was permitted to dry on one half end of each specimen while the specimen was suspended vertically before the opposite end was dipped. Admixtures B_1 and B_2 were added with the mixing water in the amounts specified in Table II.

The notation used to identify each panel consisted of the letter symbol for the treatment at the higher level. Whenever a letter symbol is absent, treatment at the zero level is indicated. Subscripts were thereby omitted except for the B_1 and B_2 treatments.

The treatments involved in each of the 48 test panels in each replication and the order in which the specimens were made are listed in Table IV.

Cyclic Exposure - All test panels were subjected to a cyclic exposure in a test chamber described in full in the final report submitted on November 14, 1953 as noted in the introduction. The panels were rearranged in a predetermined randomized pattern every 44 cycles to minimize any effect of position in the apparatus. Each cycle involved a one hour period during which the panels were submerged under water at a pressure of from 35 to 55 psig. at 70° ± 3° F. The immersion period was then followed by a three hour drying period during which air at 100° F. and 20% R. H. was blown over the specimens at about 110 ft/min.

The age of the panels when first placed in the cyclic apparatus was two months ± 1 week. Ten periods of 44 cycles each were used in accumulating the total exposure time. Each test run of 44 cycles was terminated after the drying portion of the cycle and the specimens were then placed in a controlled environment room at 50% R. H. and 70° F. for one day before resistance readings were taken.

TABLE IV

Treatments and Order of Making Test Panels for Each Replication

Batch	Test Panel	Coat. on Concrete	Coat. on Steel	Admixture	Type of Water	Cover Depth
1	(I)	None	None	None	Fresh	1/4"
1	E	Paint	None	None	Fresh	1/4"
1	F	None	Paint	None	Fresh	1/4"
1	EF	Paint	Paint	None	Fresh	1/4"
1	D	None	None	None	Fresh	1/2"
1	DE	Paint	None	None	Fresh	1/2"
1	DF	None	Paint	None	Fresh	1/2"
1	DEF	Paint	Paint	None	Fresh	1/2"
2	B_1	None	None	Plastiment	Fresh	1/4"
2	B_1E	Paint	None	Plastiment	Fresh	1/4"
2	B_1F	None	Paint	Plastiment	Fresh	1/4"
2	B_1EF	Paint	Paint	Plastiment	Fresh	1/4"
2	B_1D	None	None	Plastiment	Fresh	1/2"
2	B_1DE	Paint	None	Plastiment	Fresh	1/2"
2	B_1DF	None	Paint	Plastiment	Fresh	1/2"
2	B_1DEF	Paint	Paint	Plastiment	Fresh	1/2"
3	B_2	None	None	$CaCl_2$	Fresh	1/4"
3	B_2E	Paint	None	$CaCl_2$	Fresh	1/4"
3	B_2F	None	Paint	$CaCl_2$	Fresh	1/4"
3	B_2EF	Paint	Paint	$CaCl_2$	Fresh	1/4"
3	B_2D	None	None	$CaCl_2$	Fresh	1/2"
3	B_2DE	Paint	None	$CaCl_2$	Fresh	1/2"
3	B_2DF	None	Paint	$CaCl_2$	Fresh	1/2"
3	B_2DEF	Paint	Paint	$CaCl_2$	Fresh	1/2"

TABLE IV (cont'd.)

Batch	Test Panel	Coat. on Concrete	Coat. on Steel	Admixture	Type of Water	Cover Depth
4	H	None	None	None	Salt	1/4"
4	HE	Paint	None	None	Salt	1/4"
4	HF	None	Paint	None	Salt	1/4"
4	HEF	Paint	Paint	None	Salt	1/4"
4	HD	None	None	None	Salt	1/2"
4	HDE	Paint	None	None	Salt	1/2"
4	HDF	None	Paint	None	Salt	1/2"
4	HDEF	Paint	Paint	None	Salt	1/2"
5	HB_1	None	None	Plastiment	Salt	1/4"
5	HB_1E	Paint	None	Plastiment	Salt	1/4"
5	HB_1F	None	Paint	Plastiment	Salt	1/4"
5	HB_1EF	Paint	Paint	Plastiment	Salt	1/4"
5	HB_1D	None	None	Plastiment	Salt	1/2"
5	HB_1DE	Paint	None	Plastiment	Salt	1/2"
5	HB_1DF	None	Paint	Plastiment	Salt	1/2"
5	HB_1DEF	Paint	Paint	Plastiment	Salt	1/2"
6	HB_2	None	None	$CaCl_2$	Salt	1/4"
6	HB_2E	Paint	None	$CaCl_2$	Salt	1/4"
6	HB_2F	None	Paint	$CaCl_2$	Salt	1/4"
6	HB_2EF	Paint	Paint	$CaCl_2$	Salt	1/4"
6	HB_2D	None	None	$CaCl_2$	Salt	1/2"
6	HB_2DE	Paint	None	$CaCl_2$	Salt	1/2"
6	HB_2DF	None	Paint	$CaCl_2$	Salt	1/2"
6	HB_2DEF	Paint	Paint	$CaCl_2$	Salt	1/2"

<u>Resistance Measurements</u> - Electrical resistance measurements on each test panel were made at the end of each set of 44 cycles with a Kelvin Bridge Ohmmeter sensitive to 0.0001 ohms. All readings were corrected for temperature variations in the constant temperature room. The corrected readings are presented in Table V . Due to malfunctioning of the cylcic apparatus, the readings at the end of the first 44 cycles were not considered reliable and have been omitted from the data. Panels for which readings were discontinued were those for which the tube ends were damaged in handling so as to make the readings unreliable.

TABLE V – Replication I

Resistance Readings x 10^5 and Slope Values

Spec. No.	Resistance in Ohms x 10^5 after N Cycles									Remarks	Slope x 10^5 (b_1)	
	88	132	176	220	264	308	352	396	440		9 data points	< 9 data points *
1	1725	1726	1752	1695	1739					+	1.9550	
E	1790	1794	1793	1789	1794	1793	1810	1795	1804	b	0.9066	
F	1696	1703	1695	1693	1697	1699	1711	1699	1711	b	0.8387	
EF	1732	1735	1734	1729	1736	1735	1749	1743	1759	b	1.6046	
H	1719	1716	1719	1721	1725	1723	1737	1732	1739	b	1.6170	
HE	1684	1684	1691	1691	1704	1703	1724	1720	1736	b	3.8440	
HF	1670	1664	1667	1669	1682	1681	1701	1692	1708		3.5826	
HEF	1678	1670	1684	1681	1670	1689	1717	1702	1718		3.7781	
B_1	1657	1665	1684	1674	1679	1680	1688	1692	1696		2.4855	
B_1E	1745	1761	1779	1677	1803	1800	1821	1835	1849		7.8660	
B_1F	1725	1730	1732	1736	1758	1755	1763	1762	1770	b	3.4013	
B_1EF	1673	1677	1671	1672	1678	1678	1687	1688	1701		[illegible]	
HB_1										+		
HB_1E	1670	1674	1690	1701	1716	1749	1762	1782	1814		10.7004	7.0242
HB_1F	1670	1671	1677	1680	1688	1703	1724	1736	1743	b	5.9014	
HB_1EF	1605	1643		1667	1745						18.1562	
B_2	1681	1687	1688	1681	1685	1691	1696	1696	1706	b	1.5050	
B_2E	1656	1654	1654	1647	1651	1654	1659	1660	1666	b	0.7521	
B_2F	1717	1712	1716	1709	1710	1717	1725	1715	1728	b	0.7684	
B_2EF	1751	1746	1747	1740	1744	1744	1749	1740	1756	b	0.0928	[illegible]
HB_2	1751	1770	1832	1848	1949	2100	2229	2384	2779		54.2915	
HB_2E										+		
HB_2F	1715	1721	1754	1754	1759	1765	1780	1771	1793		5.0558	6.9621
HB_2EF	1678	1679	1685	1681	1683	1681	1691	1683	1687	b	0.5746	
D	1779	1793	1829	1820	1839					+	7.0102	
DE	1809	1845		1837	1837	1840	1854	1845	1848		1.7974	
DF	1666	1675	1669	1672	1671	1680	1695	1686	1691	b	2.1528	
DEF	1657	1665	1669	1672	[illegible]	1686	1711	1706	1720		4.6671	
DH	1709	1723	1728	1744	1736	1750	1773	1795	[illegible]	b	8.1642	
DHE	1723	1726	1730	1738	1736	1758	1795	1807			8.6020	
DHF	1692	1701	1710	1716	1715	1733	1746	1753	1773		5.4755	3.045
DHEF	1644	1672	1707							+	1.8785	
DB_1	1633	1637	1631	1635	1628	1641	1645	1641	1643	b	1.0277	
DB_1E	1679	1685	1676	1682	1674	1689	1696	1686	1693	b	1.0377	
DB_1F	1703	1702	1700	1704	1699	1694	1716	1705	1719	b	0.9254	
DB_1EF	1691	1689	1690	1698	1692	1710	1719	1713	1719	b	2.4836	2.6836
HB_1D	1687	1695	1711	1718	1719	1741	1756	1752	1767	b	5.8221	
HB_1DE	1637	1647	1693	1731	1908					+	35.574	
HB_1DF	1684	1686	1701	1702	1698	1705	1712	1708	1709		1.8726	
HB_1DEF	1713	1716	1724	1729	1734	1752	1776	1805	1827	b	8.0247	
B_2D	1718	1727	1725	1728	1728	1741	1756	1745	1769	b	3.1851	
B_2DE	1742	1730	1732	1733	1728	1737	1741	1732	1737		0.0766	
B_2DF	1593	1630	1625	1633						+	7.0472	
B_2DEF	1685	1685	1687	1692	1686	1699	1707	1695	1709	b	1.6974	
HB_2D	1833	1859	2156	2469	3558	5006				+	203.136	
HB_2DE	1814	1869	2009	2190	2387					+	66.150	
HB_2DF	1758	1759	1818	1834	1834	1858	1881	1878	1898		12.7903	
HB_2DEF	1693	1692	1723	1765	1789	1844	1901	1943	2097	b	25.1712	15.173

b No indication of damage or leaks for first 5 cycles

+ Specimens damaged at end connections.

***** Where data exists for < 9 points on the companion specimen, the slope on the given specimen was also computed using the same number of points as were available on the companion.

TABLE V - Replication II
Resistance Readings x 10^5 and Slope Values

Spec. No.	Resistance in Ohms x 10^5 after N Cycles									Remarks	Slope x 10^5 (b_1)	
	88	132	176	220	264	308	352	396	440		9 data points	< 9 data points *
1	1666	1669	1666	1662	1671	1667	1680	1666	1681	b	0.8353	0.1771
E	1722	1729	1750	1748	1768	1770	1781	1780	1795		5.0093	
F	1716	1718	1717	1714	1724	1723	1739	1728	1738	b	1.6491	
EF	1723	1725	1725	1721	1739	1744	1769	1772	1791	b	4.9082	
H	1705	1701	1704	1700	1706	1701	1718	1702	1720	b	0.8959	
HE	1684	1681	1685	1683	1692	1699	1727	1742		b	4.8645	
HF	1716	1710	1711	1710	1712	1714	1728	1725	1730		1.3447	
HEF	1666	1660	1664	1665	1666	1664	1680	1680	1685	b	1.7012	
B_1	1631	1634	1637	1629	1643	1641	1671	1671	1681	b	3.9376	
B_1E	1609	1613	1626	1625	1620	1627	1633	1625	1656	b	3.3308	
B_1F	1668	1667	1667	1669	1674	1674	1679	1673	1686	b	1.1822	
B_1EF	1780	1781	1809	1809	1801	1806	1822	1819	1831		3.1468	
HB_1	1680	1681	1685	1680	1677	1679	1687	1686	1689	b	0.5340	
HB_1E	1722	1728	1748	1745	1794					+	9.1632	
HB_1F	1758	1758	1774	1777	1780	1788	1798	1798	1825		3.8084	
HB_1EF	1686	1687	1693	1686	1687	1691	1698	1694	1694	b	0.7854	0.0598
B_2	1699	1699	1708	1710	1720	1728	1734	1731	1744	b	3.3515	
B_2E	1617	1614	1635	1617	1654	1651	1662	1654	1678	b	4.6575	
B_2F	1696	1691	1696	1689	1692	1693	1705	1700	1711	b	1.0764	
B_2EF	1769	1765	1777	1780	1810					+	5.4234	
HB_2	1273	1285	1300	1334	1385	1452	1555	1552	1641	+	33.7479	
HB_2E	1703	1708	1723	1729	1745	1777	1797	1810	1823		9.2886	
HB_2F	1835	1838	1850	1860	1877	1901				+	7.9900	
HB_2EF	1680	1683	1690	1659	1695	1700	1717		17 11	b	2.7408	
D	1687	1697	1707	1709	1719	1767	1814	1838			12.4030	4.457
DE	1674	1682	1686	1694	1693	1710	1728				4.7216	
DF	1689	1695	1687	1690	1684	1692	1706	1697	1699	b	0.8433	
DEF	1754	1767	1779	1809	1813	1824	1874	1877	1890		9.8187	
DH	1661	1675		1716	1728	1750	1770	1782	1804		10.603	
DHE	1658	1665	1687	1706	1721	1777	1821	1851	1883	b	16.1801	
DHF	1613	1716	1720	1716						+	18.7864	
DHEF	1723	1735	1751	1766	1767	1794	1820				3.2384	6.9253
DB_1	1706	1709	1704	1708	1703	1714	1718	1711	1716	b	0.7786	
DB_1E	1692	1695	1693	1698	1689	1700	1704	1696	1700	b	0.5792	
DB_1F	1691	1692	1689	1692	1686	1699	1704	1696	1701	b	0.8740	
DB_1EF	1655	1659	1661	1717	1729	1768	1796			+	6.8697	
HB_1D	1627	1647	1661	1761	1839					+	31.154	
HB_1DE	1705	1715	1767	1829	1955	2094	2302	2542	2789	b	63.9104	33.72
HB_1DF	1767[a]	1719	1727	1730	1733	1742	1756	1751	1754	b	3.1588	
HB_1DEF	1685	1692	1699	1704	1704	1718	1726	1725	1734	b	3.5351	
B_2D	1699	1704	1703	1706	1698	1708	1710	1702	1709	b	0.4746	
B_2DE												
B_2DF	1711	1712	1715	1716	1707	1719	1722	1723	1733	b	1.3367	-0.246
B_2DEF	1774	1775	1777	1781	1778	1805	1821	1824	1839	b	4.7932	
HB_2D	1737	1755	1972	1847[a]	2398					b	78.8125	
HB_2DE	1826		1920	2058	3242						123.4065	
HB_2DF	1717	1721	1732	1792	1770	1816	1840	1829	1857		11.3701	
HB_2DEF	1714	1725	1788	1856						+	25.5867	

b No indication of damage or leaks for first 5 readings.

\+ Specimens damaged at end connections.

* Where data exists for < 9 points on the companion specimen, the slope was also found using the same no. of points as were available on the companion.

a These obviously incorrect readings were omitted in determining the slopes.

Statistical Analysis: As a result of the aforementioned mechanical difficulties and others, certain "holes" were left in the data intended for a statistical analysis. Consequently, it was decided to select a portion of the data which was entirely free from these difficulties (See items b in Table V) and which was suitable for computer programming. These data, (i. e., the first five readings of the specimens denoted by (b) in the remarks column) were analyzed by fitting straight lines to a plot of log R/R_o* versus number+ of cycles. The slopes of these lines correspond to the corrosion rates and were the basic variables used in the analysis. Due to the large number of missing data points, a non-orthogonal analysis resulted and a summary of this analysis is presented in Table VI.

TABLE VI

50 Specimen Analysis

(Items b in Table V)

Source	Degrees of Freedom	Sums of Squares	Mean Square	F Ratio
Treatments	33	23,228.67	703.90	123.9
Main Effects (ME) Unadjusted	6	4,010.99	668.50	117.7
Two Factor Interaction Adjusted for ME	14	9,908.45	707.75	124.6
Higher Interaction Adjusted for ME and Two Factor Interaction	13	9,309.23	716.10	126.1
Error	16	90.88	5.68	
Total	49	23,319.55		

The 50 specimen analysis summarized in Table VI shows that sums of squares for the main effects, for the two factor interactions, and for the higher order actions are relatively of the same magnitude, and that their F-factors are all very large. The main effects taken alone, or even the main effects plus the two-factor interactions, do not dominate the total sums of squares for the 33 treatments, even though their large F factors indicate significance at a very high level. Hence, the two and higher order interactions mask the main effects.

Taken as a whole the analysis seems to indicate that the test specimen slopes from each of the 34 treatments represented should be considered separately. A perusal of the slopes shows that this indeed is the case. Four observations contribute almost all of the variation in the experiment without being replicated, (i. e., their corresponding values for the other replication are missing).**Therefore, it was decided to re-analyze the data

* Logarithm of the ratio of the resistance after N cycles to the original resistance.

\+ A coded value of the number of cycles was actually used.

** Replication I, HB_2DEF; Replication II, DHE, HB_1DE, and HB_2D.

omitting these observations as is done in Table VII.

TABLE VII

46 Specimen Analysis
(Items b Table V omitting 4 specimens)

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F-Ratio
Treatments	29	296.8015	10.2345	1.76
Main Effects Unadjusted	6	28.9948	4.8325	.85
Interactions Adjusted	23	267.8067	11.6432	2.05
Error	16	90.8750	5.6797	
Total	45	387.6765		

This analysis verified the conclusions reached above, and by no significance shows the tenuous nature of the evidence of the four observations. Interactions are the only place where any significance has a possibility of showing itself. This leads, of course, to the conclusion above; i. e., any information contained in the experiment is on an individual test specimen basis.

Consequently, an analysis of the individual specimens was undertaken. In this analysis, all of the data were considered, for an examination of the data and specimens which had leaked at some stage during the test indicated no detrimental effects resulting therefrom. The method of least squares was used to obtain the slope of best fit for each specimen and the results of this analysis are discussed in the following section.

Discussion of Results: Although the statistical analysis did not indicate significance in the data according to a linear logarithmic assumption, much of the data showed little deviation from a smooth curve when plotted. Such data can undoubtedly be represented by non-linear logarithmic functions but little could be gained for comparison purposes. Thus it was decided to use values of b_1, the slope of the linear logarithmic curve of best fit shown in Table V.

A brief examination of the data indicates that the greatest corrosion occurred in the mixes containing salt water and calcium chloride. In order to include these groups for comparison, only the interactions between salt water and admixtures were considered. The results of these calculations are presented in Table VIII. Each value in this table is an average of all slopes (b_1) at the indicated levels. For instance in the H x E interaction, the value 2.3643 is the average of the slopes of the 24 specimens tested at the H_0E_0 level, etc. The results of the comparisons are as follows.

<u>H x E Interaction</u> - Referring to Table VIII, it is apparent that the most significant feature revealed by the H x E interaction is the corrosive influence of the salt water. With no concrete coating, the corrosion rate is increased from 2.3643 to 23.0073 and with the concrete coating, the corrosion rate is increased from 3.3488 to 18.4003. This effect is apparent throughout the following comparisons and will not be discussed further here. The increased corrosion of the fresh water mixes and decreased corrosion of the salt water mixes resulting from the concrete coating are interpreted as unimportant here since the quantitative influence is small relative to the salt water action.

<u>H x F Interaction</u> - The steel coating provided no significant protection against corrosion of the fresh water mixes but materially reduced corrosion of the salt water mixes.

<u>H x B Interaction</u> - Both Plastiment and $CaCl_2$ slightly reduced corrosion in the fresh water mixes but accentuated corrosion (especially the $CaCl_2$) in the salt water mixes.

<u>H x D Interaction</u> - Increased cover depth was not beneficial to the fresh water mixes and was severely detrimental to the salt water mixes.

<u>B x E Interaction</u> - Without a concrete coating, plastiment had no significant effect whereas $CaCl_2$ increased the corrosion severely. An undesirable interaction was noted between the plastiment and the concrete coating. The concrete coating, however, reduced corrosion in the $CaCl_2$ mix.

<u>B x F Interaction</u> - Both plastiment and $CaCl_2$ caused increased corrosion in the uncoated specimens. By coating the steel rods, a significant reduction in corrosion was effected.

<u>B x D Interaction</u> - Increased cover depth increased corrosion in all mixes as did plastiment and calcium chloride.

<u>H x E x B Interaction</u> - In general, the concrete coating exhibited no significant effect on the mixes containing admixtures except for an undesirable interaction with plastiment. Both plastiment and $CaCl_2$ (especially $CaCl_2$) increased corrosion in the salt water mixes with the concrete coating. $CaCl_2$ also increased corrosion for the salt water mixes without concrete coating.

<u>H x F x B Interaction</u> - The steel coating had no significant effect upon the fresh water mix corrosion but materially reduced the corrosion in all the salt water mixes, especially those containing plastiment and $CaCl_2$. The undesirable interaction between both of the admixtures and the salt water is again apparent.

<u>H x B x D Interaction</u> - While increased cover depth increases corrosion in the fresh water mixes without admixtures, this corrosion can be reduced by adding plastiment. The undesirable interaction between the admixtures and salt water, however, is intensified by increasing the cover depth.

The undesirable effect upon corrosion of salt mixing water is exhibited throughout the data just described and so was not discussed in connection with the interactions.

TABLE VIII

Average Values of $b_1 x 10^5$

H x E	E_0	E_1	H x F	F_0	F_1
H_0	2.3643	3.3488	H_0	2.7567	2.6886
H_1	23.0073	18.4003	H_1	32.1423	7.3836

H x B	B_0	B_1	B_2
H_0	3.8199	2.3583	2.3914
H_1	5.9098	12.1196	42.0820

H x D	D_0	D_1	B x E	E_0	E_1
H_0	2.4006	3.1915	B_0	2.8848	4.8450
H_1	7.2966	32.2668	B_1	3.9327	10.5452
			B_2	27.2399	17.2334

B x F	F_0	F_1	B x D	D_0	D_1
B_0	5.5880	4.0157	B_0	2.3958	7.2714
B_1	10.5533	4.1207	B_1	4.2473	10.4762
B_2	36.4272	6.9708	B_2	7.9022	35.4396

TABLE VIII (Continued)

H x E x B	E_0			E_1		
	B_0	B_1	B_2	B_0	B_1	B_2
H_0	3.4609	1.3265	2.3056	4.1791	3.3901	2.4771
H_1	6.30866	6.5389	52.1742	5.5109	17.7003	31.9898

H x F x B	F_0			F_1		
	B_0	B_1	B_2	B_0	B_1	B_2
H_0	4.3297	2.6302	1.7503	3.3103	2.5862	2.1693
H_1	6.8463	18.5764	71.1041	4.7231	5.6553	11.7724

H x D x B	D_0			D_1		
	B_0	B_1	B_2	B_0	B_1	B_2
H_0	2.2131	3.3945	1.5932	5.4267	1.8214	2.3263
H_1	2.5785	5.1002	14.2112	9.1161	19.1314	68.5529

Test results ind[illegible] that

Summary - The data presented in this report seem to justify the following conclusions:

(1) Salt water alone and interactions between salt water and plastiment and $CaCl_2$ respectively, produced the greatest amounts of corrosion ~~in the foregoing tests. From the H x B interaction table,~~ the corrosion rate caused by salt water is 1.55 times that exhibited by fresh water mixes, a salt water with plastiment mix causes 5.14 times the corrosion rate caused by fresh water mix with no plastiment, and a salt water mix with calcium chloride causes 17.6 times the corrosion rate exhibited by a fresh water mix with no calcium chloride,

(2) In general, no significant reduction in corrosion rates is achieved through the use of the concrete coating employed except when $CaCl_2$ is used, In some cases, interactions between the coating, admixtures, and salt water increase the corrosion rate. The same may be said for increased cover depth except that when plastiment or $CaCl_2$ are employed in fresh water mixes, increased cover depth will reduce corrosion.

and (3) For protection against the corrosion for salt water mixes, ~~(Item 1 above),~~ the steel coating employed ~~herein~~ produced remarkable results, in some cases reducing corrosion by 600%, In fresh water, however, the beneficial effect of the steel coating was only slight.

~~(4)~~ In view of the difficulties encountered with the end connections of the specimens described earlier in the report, it is strongly recommended that a one piece drawn tube, a drawn tube with solid shrunk fit ends, or some other suitable tube design be employed in future tests.